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NASA'S SPACE LAUNCH SYSTEM ADVANCED BOOSTER
ENGINEERING DEMONSTRATION AND/OR RISK REDUCTION EFFORTS

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The National Aeronautics and Space Administration (NASA) formally initiated the Space Launch System (SLS) development in September 2011, with the approval of the program's acquisition plan, which engages the current workforce and infrastructure to deliver an initial 70 metric ton (t) SLS capability in 2017, while using planned block upgrades to evolve to a full 130 t capability after 2021. A key component of the acquisition plan is a three-phased approach for the first stage boosters. The first phase is to complete the development of the Ares and Space Shuttle heritage 5-segment solid rocket boosters (SRBs) for initial exploration missions in 2017 and 2021. The second phase in the booster acquisition plan is the Advanced Booster Risk Reduction and/or Engineering Demonstration NASA Research Announcement (NRA), which was recently awarded after a full and open competition. The NRA was released to industry on February 9, 2012, with a stated intent to reduce risks leading to an affordable advanced booster and to enable competition. The third and final phase will be a full and open competition for Design, Development, Test, and Evaluation (DDT&E) of the advanced boosters. There are no existing boosters that can meet the performance requirements for the 130 t class SLS. The expected thrust class of the advanced boosters is potentially double the current 5-segment solid rocket booster capability. These new boosters will enable the flexible path approach to space exploration beyond Earth orbit (BEO), opening up vast opportunities including near-Earth asteroids, Lagrange Points, and Mars. This evolved capability offers large volume for science missions and payloads, will be modular and flexible, and will be right-sized for mission requirements. NASA developed the Advanced Booster Engineering Demonstration and/or Risk Reduction NRA to seek industry participation in reducing risks leading to an affordable advanced booster that meets the SLS performance requirements. Demonstrations and/or risk reduction efforts were required to be related to a proposed booster concept directly applicable to fielding an advanced booster. This paper will discuss, for the first time publicly, the contract awards and how NASA intends to use the data from these efforts to prepare for the planned advanced booster DDT&E acquisition as the SLS Program moves forward with competitively procured affordable performance enhancements.

I. BACKGROUND

NASA Authorization Act

The NASA Authorization Act of 2010 included NASA development of the heavy-lift Space Launch System (SLS), the Orion Multi-Purpose Crew Vehicle (MPCV), and Ground Systems Development and Operations (GSDO) as the core elements of NASA's human space exploration architecture. The Act specified initial and evolved SLS capabilities to support early and future missions beyond low-Earth orbit (LEO), including cis-lunar space, while also providing a series of minimum capabilities. The SLS vehicle would: initially lift 70 t to LEO and be evolvable to 130 t or more; lift the Orion MPCV; and serve as a backup system for supplying and

supporting cargo and crew delivery requirements for the International Space Station (ISS) in the event that such requirements are not met by available commercial or partner-supplied vehicles.

NASA and the United States (U.S.) Congress announced the development of SLS on September 14, 2011. This specific architecture was selected largely because it utilizes an evolvable development approach, which allows NASA to better reconcile typical development cost curves with the reality of a non-increasing budget. This architecture also enables NASA to leverage existing capabilities and lower development costs by using such assets as Saturn- and Shuttle-derived engines, and, for the initial configuration missions, Shuttle-derived solid motors. But, for the first time, "legacy" systems included

propulsion and control technologies developed in this century. The new launch capability would leverage experience, including contractual experience, regardless of heritage. Existing contract vehicles were included to benefit from past investments, and acquisition plans reflect this direction.

While the new launch capability would also include new spacecraft and payload adapter and fairing designs, it would be comprised, to the greatest extent practicable, of proven systems that possess performance history. However, plans to utilize liquid engines derived from existing designs that are in some cases already in inventory also means that bold missions to new destinations would require boosters with a greater capability than existing or planned solid motors could provide. This new heavy-lifter would eventually – after the first two flights, according to current manifests – need a new booster. An acquisition plan was developed to utilize existing contracts as well as new procurements for systems comprising the evolutionary concept.

The design selected by the Agency was closest, from among hundreds considered, to fitting within a non-increasing annual budget profile, while meeting system-level requirements. This was due to several factors, such as the rocket’s relatively simple design (i.e., minimum number of hardware elements to achieve the desired performance) and the plan to start with existing Agency hardware assets and other elements that were well into the development cycle.

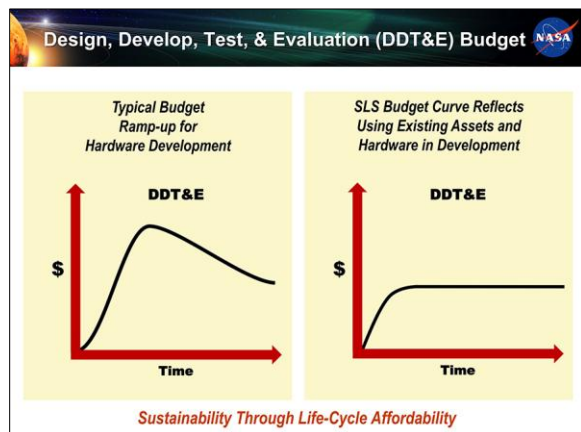


Fig. 1: Development Budget Curve.

This strategy responds to a nontraditional DDT&E budget curve, which keeps the system affordable and sustainable over the decades that an endeavor such as this will span. As such, production and operations

costs are also considered as independent variables in trade studies, along with nonrecurring development costs.

Flexible Path

A “flexible path” approach to space exploration was also part of the NASA Authorization Act of 2010. This would open up vast opportunities for new destinations, including near-Earth asteroids and Mars. This followed the 2009 Review of U.S. Human Spaceflight Plans Committee Report. The committee, chaired by Norman Augustine, recommended a “flexible path” as one of three potential options for human exploration BEO.

A flexible path, in the words of the Augustine Commission, represents a different type of exploration strategy, one that would allow humans to learn how to live and work in space, to visit small bodies, and to work with robotic probes on planetary surfaces. It would provide the public and other stakeholders with a series of interesting “firsts” to keep them engaged and supportive. Most important, because the path is flexible, it would allow for many different options as exploration progresses, including a possible return to the Moon’s surface or a continuation directly to the surface of Mars.*

SLS is a key cornerstone of the flexible path approach to space exploration, and the SLS architecture and block design approach reflect this strategy.

II. ARCHITECTURE OVERVIEW

SLS Decision Rationale

Ultimately, a carefully considered architecture decision met policy and law while leveraging development progress, the U.S. aerospace industry’s workforce experience, existing assets, and unique infrastructure. The flexible path/capability-driven framework decision for the SLS vehicles maintains U.S. leadership in liquid oxygen/liquid hydrogen (LOX/LH2) propulsion technology by leveraging experience within the Agency and its industry partners on the RS-25 core stage engines and the J-2X upper stage engine. The capability-driven

* Review of U.S. Human Spaceflight Plans Committee Report, October 22, 2009.
http://www.nasa.gov/pdf/396093main_HSF_Cmte_FinalReport.pdf

framework establishes a fixed central design path, with the logical use of existing strengths in design and modern manufacturing approaches. It also harnesses the existing knowledge base, skills, infrastructure, workforce, and industrial base for state-of-the-art systems.

Minimizing unique configurations during vehicle development, the evolutionary path to a 130 t vehicle allows for incremental development, enabling progress to be made even within constrained budgets, while also allowing for early flight certification for the Orion MPCV. Thus, SLS may be configured for Orion or other large cargo payloads, providing a flexible/modular design and a system for varying launch needs.

Affordability

With the retirement of the Space Shuttle Program and cancellation of the Constellation Program, the Agency is funding commercial activities that will yield a commercial cargo capability during the transition to NASA's new human space exploration architecture. In a resource-constrained environment, SLS must fit within its resource envelope (e.g., budget, workforce, and facilities). The SLS Program is incorporating affordability initiatives and lean practices as it strives to deliver a safe, affordable, flexible, and sustainable long-term national capability.

Built on the fundamental principle that affordability begins with accountability, the evolvable development approach has adopted an innovative testing philosophy to meet requirements. For example, delta qualification testing will only be undertaken where there is a significant shortfall in the original item qualification limits and where qualification by other means is not possible. Significant cost savings can be realized by focusing development efforts on credible failure modes using probabilistic methods rather than utilizing development approaches that baseline multiple safety margins across multiple disciplines. Further, an 8.4-meter common diameter for both core and upper stages could yield a 20-percent reduction in DDT&E costs, a simplified design, common tooling and facilities, and a reduced number of suppliers and oversight.

SLS booster design and development activities have also employed a value stream mapping process to evaluate production of 5-segment solid rocket

boosters, resulting in hundreds of changes that eliminate sources of waste and hardware moves and improve cycle time by nearly half.

And while effectively managing requirements and leveraging existing capabilities, including LOX/LH2 propulsion infrastructure, manufacturing facilities, and launch sites, the evolvable development approach is infusing new design solutions for affordability. For instance, a risk-based Government insight/oversight model comes with the realization that significant cost can be driven by the level of Government-contractor interaction, the number of products and deliverables requested through the procurement process, and the number and type of requirements. This new insight/oversight model is a significant change to the philosophy and culture of previous NASA human spaceflight programs.

Right-sized documentation and standards may result in a reduction in the majority of data requirements and program documents from the Ares Projects, as well as better implementation of industry practices and tailored NASA standards. Lean, integrated teams with accelerated decision making provide simple, clear technical interfaces with contractors; an integrated Systems Engineering and Integration (SE&I) organization; empowered decision makers at all levels; fewer control boards and streamlined change processes; use of heritage hardware and manufacturing solutions; and the ability to maintain adequate management reserves controlled at lower levels.

Architecture Description

The SLS Program is comprised of multiple elements that will be developed and integrated into an evolved launch vehicle designed to enable exploration missions beyond LEO. As the orbital delivery system for this human and cargo space exploration architecture, the SLS Program will provide the necessary functions of crew and cargo launch; vehicle staging; vehicle communication with the Orion MPCV, GSDO, and U.S. Air Force Eastern (launch) Range; vehicle fault management; LEO or trajectory insertion; and payload separation at the destination orbit or trajectory.

The SLS vehicle concept originates from the family of Saturn launch vehicles used during the Apollo Program, as well as from designs and technologies from the more recent Space Shuttle and Constellation Programs. The reprioritization of affordability as a

key measure of program success has led NASA to re-evaluate past heavy-lift launch vehicle studies to focus on design concepts that can support a variety of mission sets defined by evolving space exploration architecture capabilities within a capability-driven framework. Accordingly, NASA's system architecture for exploring space is developed incrementally to support missions with increasing needs for system capability. The SLS architecture is being developed around a low rate of missions, so any additional missions could yield affordability benefits. NASA's capability-driven framework and SLS vehicle concept is shaped by the incremental steps shown in Figure 2.

SLS Block Upgrade Strategy

The SLS block upgrade strategy, shown in Figure 3 and described on the following page, reflects the

scope of the capability-driven framework by incrementally and practically increasing the performance of the launch vehicle one block at a time. The performance thresholds of 70 t, 105 t, and 130 t are achieved respectively through the development of Block 1, followed by the upgrade of Block 1 to Block 1A then to Block 2. This strategy relies on the use of existing technology for Block 1, followed by new boosters for Block 1A, and an upper stage for Block 2. The upgrade process will also depend on improving processes and the modification of other components, such as engines and materials. The SLS Program also recognizes that as new technologies are realized, the configuration of future blocks may be revised.

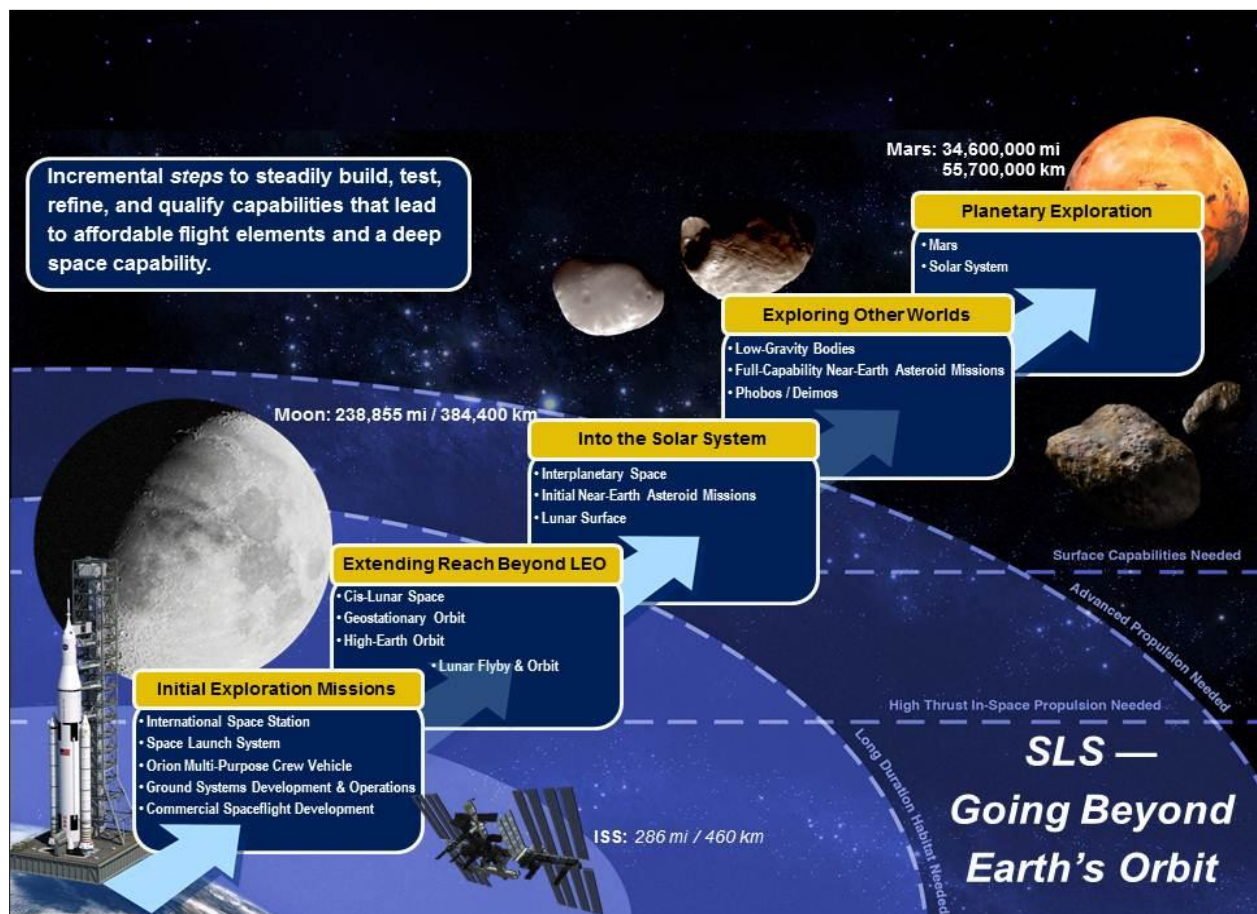


Fig. 2: SLS is a national asset for stakeholders and partners.

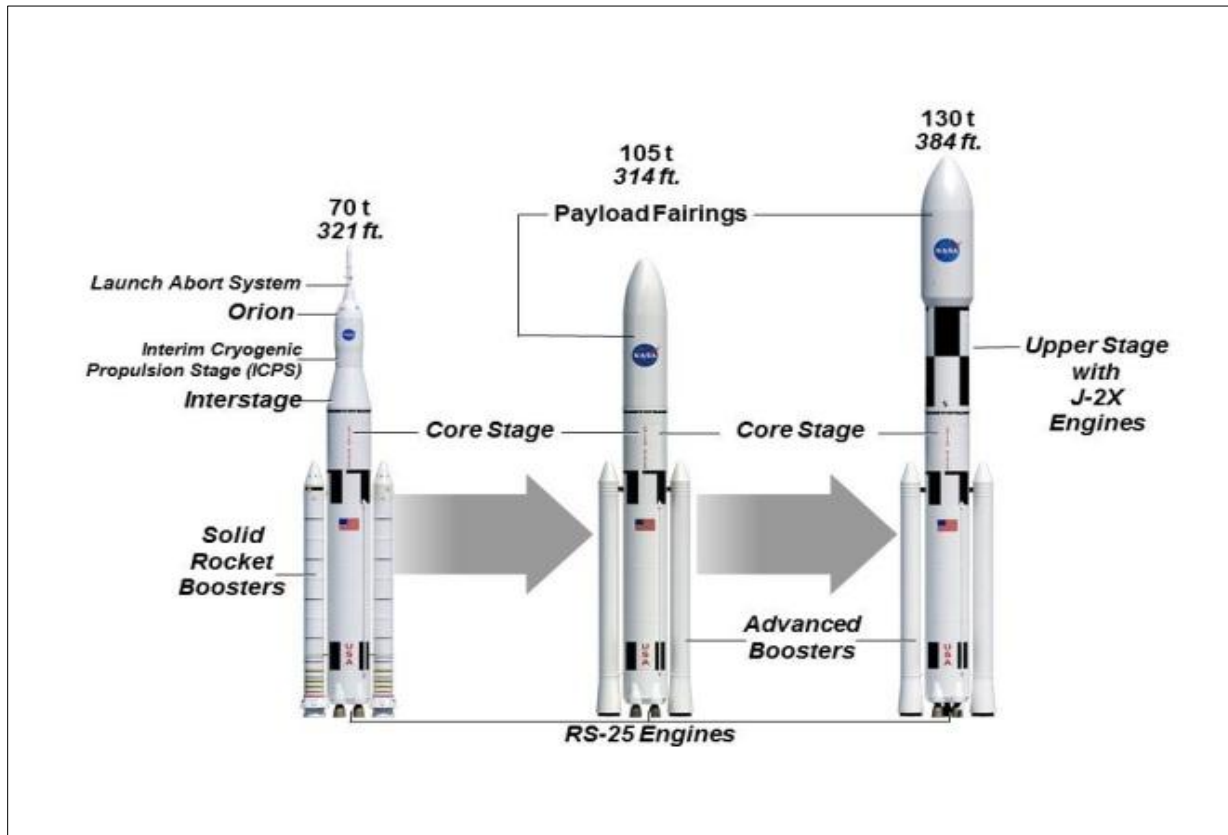


Fig. 3: Initial and evolved SLS concepts (From left to right, Blocks 1, 1A, and 2).

The Block 1 vehicle:

- Provides a minimum of 70 t of payload mass capability to an orbit of -47×130 nautical miles (nmi) at a 28.5-degree inclination.
- Features a 1.5-stage configuration with an 8.4-meter diameter common core stage.
- Utilizes four Space Shuttle Main Engine RS-25 engines for the core stage.
- Utilizes two Ares I-derived 5-segment SRBs.
- Includes an interim cryogenic propulsion stage (ICPS) for Orion MPCV missions.

The Block 1A vehicle:

- Provides a minimum of 105 t of payload mass capability to an orbit of -47×130 nmi at a 28.5-degree inclination.
- Features a 1.5-stage configuration with the 8.4-meter diameter Block 1 common core stage.

- Utilizes the RS-25 engine for the common core stage.
- Incorporates a new liquid or upgraded solid booster design.
- Includes an optional payload fairing and adapter for cargo missions.

The Block 2 vehicle:

- Provides a minimum of 130 t of payload mass capability to an orbit of -47×130 nmi at a 28.5-degree inclination.
- Features a 2.5-stage configuration with 8.4-meter diameter core stage and upper stage.
- Is derived from the Block 1/1A common core stage and LOX/LH2 upper stage with the J-2X engine system.
- Incorporates the Block 1A booster design.
- Includes a 10-meter diameter payload fairing and adapter.

III. ACQUISITION STRATEGY

Acquisition Strategy

The SLS block upgrade-based program architecture discussed in Section II was selected based on an analysis-of-alternatives with respect to the SLS Program tenets, capability requirements, and needs, goals, and objectives. The block approach allows NASA to mitigate the high cost of development activities early in the program by leveraging existing/proven technologies to satisfy early design reference missions associated with transporting 70 t for insertion into LEO. Additionally, this architecture enables NASA to leverage the modular design of the SLS launch vehicle to optimize the business factors related to a diverse variety of design reference missions.



Fig. 4: A 5-segment booster development motor on the test stand.

Advanced Booster Acquisition Process

With the timeline defined by budgets and DDT&E, the acquisition of an evolved booster include an initial Engineering Demonstration and Risk Reduction phase during which competition drives innovation during concept definition and early validation. A singular prerequisite for qualification is a plausible concept for consideration in the follow-on DDT&E phase. Engineering Demonstration and Risk Reduction efforts theoretically includes ideas for reducing development costs and increasing overall affordability. Regardless of whether the propellant is liquid or solid, boosters attach to the core stage at the same locations, further promoting interchangeability and flexibility.

SLS maximizes U.S. aerospace workforce and capabilities by employing a three-phased boosters approach that delivers near-term initial capabilities and spurs competition for evolved capabilities. For Phase 1, NASA is using the Space Shuttle's heritage SRBs as a starting point in the design and development of boosters for the SLS initial capability. This minimizes technical risks and development costs. The new 5-segment motor, an in-scope modification to the existing contract with Alliant Techsystems (ATK), provides a greater total specific impulse with improved, more environmentally friendly materials. To date, three development motors have been successfully static tested by NASA and ATK in Promontory, Utah[†], with a qualification motor test scheduled for spring 2013.

Phase 2 features a Block 1A/Block 2 engineering and risk reduction for advanced boosters via an NRA, with a full and open competition in fiscal year (FY) 12 and award by FY13. The intent of this effort is to reduce risks, leading to an affordable and reliable advanced booster that meets the evolved capabilities of SLS (used in flights beyond 2021), as well as enable competition by mitigating targeted advanced booster risks to enhance SLS affordability. The advanced booster proposals offer improved performance by either liquid or solid propulsion. Key concepts of this NRA are that each proposal must include an advanced booster concept in response to a set of top-level performance requirements that meet the SLS vehicle mission requirements; the engineering demonstration and risk reduction must relate to each proposer's advanced booster concept(s); and the NRA is not prescriptive in defining engineering demonstration and/or risk reduction, allowing each proposer maximum flexibility.

Ultimately NASA selected five proposals to develop engineering demonstrations and risk reduction concepts for SLS: Subscale Composite Tank Set, Northrop Grumman Systems Corporation Aerospace Systems; Full-Scale Combustion Stability Demonstration, Aerojet General Corporation; F-1 Engine Risk Reduction Task, Dynetics, Inc.; Structures Risk Reduction Task, Dynetics, Inc.; and Integrated Booster Static Test, ATK Launch Systems,

[†] ATK Press Release, September 8, 2011.
<http://atk.mediaroom.com/index.php?s=25280&item=60330>

Inc. These proposals are discussed in more detail in Section IV of this paper.

Phase 3 features a full and open competition for DDT&E, with a request for proposal (RFP) targeted for FY15.

IV. ADVANCED BOOSTER DETAILS

The Advanced Booster NRA was written to solicit industry response in the form of an overall vehicle concept to meet the performance requirements also provided as part of the NRA. Additionally, each proposal should focus on critical risks associated with the proposed vehicle concept and to identify and describe in detail the highest ranking risk reduction activities that fit within the stated objectives of the NRA - enhanced affordability and improved reliability - while meeting the performance requirements.

The NRA was non-prescriptive by design in an effort to encourage the proposers to think outside the box. Proposers were allowed to suggest ideas that challenge the existing SLS requirements if significant affordability rationale was provided.

Use of the NRA framework, as opposed to the standard RFP, placed the “best value” option in the hands of the proposer and provided maximum engineering design flexibility to explore every viable advanced booster option for the SLS Program. Additionally, the flexibility allowed through the NRA framework served to enable competition by mitigating targeted advanced booster risks to enhance SLS affordability.

In response to the Advanced Booster NRA, seven proposals were received on April 9, 2012. The proposals were evaluated in accordance with the Advanced Booster NRA solicitation, with evaluation criteria consisting of three equivalent factors: (1) Relevance to NASA Objectives, (2) Intrinsic Merit, and (3) Price.

The outcome of the NRA evaluation was the selection of four of the seven companies, among which a total of five Engineering Demonstration and Risk Reduction tasks were selected to be funded.

Performance of the Northrop Grumman Systems Corporation Aerospace Systems subscale composite tank task will provide experience with composite tank/airframe manufacturing techniques, in particular

out-of-autoclave cure. Use of composite structural elements help reduce weight, which in turn can improve performance. The tank will be manufactured as two halves, reducing the number of joints and increasing reliability. The use of an “in-situ” manufacturing process also provides the ability to perform multiple processing steps (fabricate, outfit, and test) within a single facility footprint, thereby reducing the amount of manufacturing space required.

The Aerojet General Corporation’s Full-Scale Combustion Stability Demonstration task includes a high-performance booster using an Oxygen Rich Staged Combustion (ORSC) cycle. The ORSC engine is potentially a good candidate for U.S. Air Force applications, which would provide additional affordability benefits by distributing design, development, and production costs between the U.S. Air Force and NASA. The high-performance aspect of the ORSC cycle provides a performance advantage over other systems by allowing a smaller booster for a given thrust level. An ORSC cycle that uses refined petroleum (RP) affords significant advantages in both performance and operations. On the performance side, the use of RP allows for smaller booster due to the net density impulse of RP over hydrogen. Operational advantages of using RP are realized because it exists at ambient conditions, making handling, transportation, and storage more affordable.

The U.S. Air Force Research Laboratory (AFRL) is currently investigating ORSC technologies as part of its Hydrocarbon Boost (HCB) Program, a 250k technology demonstration program that includes a hardware contract with Aerojet General Corporation and testing at Edwards Air Force Base. In addition to being the prime contractor for the HCB Program, Aerojet General Corporation was selected for negotiations under the NASA Advanced Booster Development and/or Risk Reduction contract to study combustion stability. NASA and AFRL recognize the mutual benefit from collaboration and exchange of information on ORSC and are currently evaluating the potential synergies. These opportunities may include exchange of designs, analyses, and test hardware and data. Because Aerojet General Corporation is the prime contractor for the HCB Program and a potential Advanced Booster Development and/or Risk Reduction task, there may be additional efficiencies and synergies executing complementary technology development activities under the two distinct programs or pooling resources to further develop the technology.

Two tasks were selected from the Dynetics proposal. The F-1 Engine risk reduction task, aimed at lowering costs while improving reliability, uses a gas generator (GG) cycle with a redesigned injector plate. Using modern manufacturing techniques such as Selective Laser Melting to produce an injector plate could reduce production cost by as much as 50 percent and significantly reduce the number of parts. Other manufacturing enhancements include the hot isostatic press bonding process, which will be used to produce a new main combustion chamber and wall nozzle, replacing heritage “hand-crafted” components like the tube wall thrust chamber assembly, nozzle extension, and turbine exhaust manifold.

The second task, structures risk reduction, focuses on airframe affordability. One major benefit of using multiple higher-thrust class engines is that the concept provides sufficient performance margin to allow focus on a simpler, more robust booster tank structural design. Increased cost and schedule risk associated with complex structural design production methods and tooling, necessitated by the use of lighter-weight, stronger materials, can be mitigated. Design of the booster tank structure using Al-2219 and employment of existing yet underutilized advanced manufacturing capabilities at NASA’s Marshall Space Flight Center serves to enhance affordability.

The ATK task, Integrated Booster Static Test, was selected on the basis of enhanced affordability and reliability gains. This task targets the majority of advanced booster risks via a near-full scale (92 inch diameter) integrated test. The ATK approach is anchored in the successful 30-year heritage of the Reusable Solid Rocket Motor as part of the Space Transportation System program. The use of advanced manufacturing techniques and streamlined processes, combined with an innovative design, could result in significant cost savings over the current five-segment SRB.

This task demonstrates innovations for a solid-fueled booster and addresses a significant number of the key risks associated with low-cost solid propellant boosters, particularly in the following areas: composite case health monitoring system development and test; advanced materials in liner and insulation; advanced propellant and grain design; and composite flex bearing design. Improvements in the above areas, combined with automated propellant processing, impact detection for composite case

structure, and incorporation of electric thrust vector control, combine to provide an affordable demonstration that will anchor models and predictions for the full-scale advanced booster.

V. SUMMARY

The Advanced Booster NRA tasks outlined above are multi-disciplined. While the NRA required the proposer to provide an overall concept, it was only used to provide a boundary for the proposer and NASA with respect to risk reduction. Moving forward, the focus during the NRA execution period will only be on the risk reduction tasks themselves. Exercising these tasks will provide advancements in manufacturing/fabrication techniques for composite structures for both component (nozzles) and full airframe (tank/case) structures.

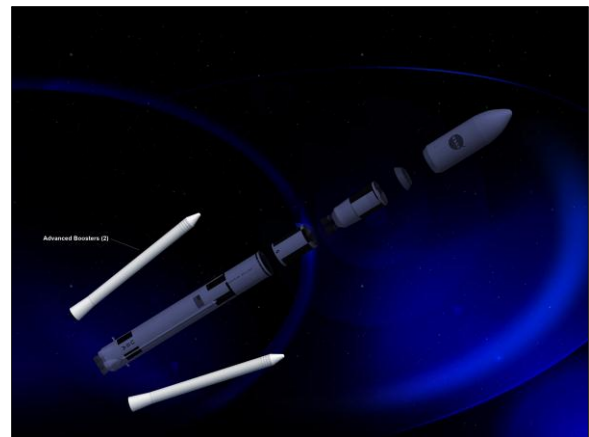


Fig. 5: Artist’s concept of SLS advanced boosters

These tasks reduce risks on both the gas generator and oxygen-rich staged combustion engine cycles, and the use of new materials and processes. The knowledge gained in studying liquid engines could provide a commonality link between the U.S. Air Force and NASA to distribute life cycle costs, thereby enhancing affordability. Likewise, these tasks include continued exploration in the area of solid propellant rocket boosters. Although NASA has extensive experience in this area, there is potential for significant benefit with advancements in composite construction propellant-liner-insulation, propellant processing techniques, lightweight materials for nozzles, and use of modern electronics with electric thrust vector control.

The Advanced Booster NRA is providing a significant opportunity for NASA to learn and

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demonstrate the capabilities required to ensure success of the SLS system. Based on the Engineering Demonstration and/or Risk Reduction tasks that have been selected, NASA is poised to accomplish our goal of reducing the risks for SLS advanced booster in a competitive environment. Execution of the advanced booster tasks will provide the foundation

required to lead NASA to an evolved capability needed for the SLS system.



Fig. 6: Artist's concept of SLS 130 t vehicle launching from the Kennedy Space Center.